

## Probing Light Sbottoms with B Decays

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### Abstract

We discuss recently reported experimental hints for a bottom squark with mass around 3.5 GeV decaying as  $\tilde{b} \rightarrow c\ell\tilde{\nu}^*$ . We correlate the sbottom lifetime with the decay rates for  $b \rightarrow \tilde{b}\nu\tilde{\nu}^*$  and  $b \rightarrow \tilde{b}\bar{\nu}\tilde{\nu}$  in the framework of a minimal supersymmetric model extended by right-handed (s)neutrinos. Confronting our results with the well-measured semileptonic branching ratio of  $B$  mesons we conclude that the light sbottom interpretation of the experimental anomalies is ruled out, unless  $m_b \leq m_{\tilde{b}} + m_{\tilde{\nu}}$ .

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### I. INTRODUCTION

Supersymmetry predicts the existence of scalar partners for all Standard Model fermions. Scalar quarks are usually assumed to be heavy, based on direct searches at LEP [1,2] and the Tevatron [3,4]. However, most of the collider searches rely on a large missing (transverse) energy cut, and supersymmetric particles with small masses may escape detection, because they lead to softer events with too little missing energy. On the other hand, decays of heavy Standard Model particles provide a powerful tool to search for such light superpartners. No new particles have been found in  $Z$  decays at LEP-I and SLD. Hence supersymmetric scenarios with particle masses below  $m_Z/2$  are constrained, as their couplings to the  $Z$  boson must be very small. Recently the ALEPH collaboration has reported experimental hints for a light sbottom squark with a mass around 4 GeV and a lifetime of 1 ps [5]. Its experimentally detected decay mode appears as a chargino-mediated decay into a charm quark, a lepton and an essentially massless anti-sneutrino [5]. These findings have prompted a reanalysis of an old anomaly in the MARK-I data for the cross section of  $e^+e^- \rightarrow \text{hadrons}$ : the existence of a squark with a mass between 3.6 and 3.7 GeV is found to bring the measured cross section into agreement with the theoretical prediction [6]. Since the coupling of the  $Z$

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boson to sneutrino mass eigenstates is constrained by the measured invisible  $Z$  width, one must supplement the Minimal Supersymmetric Standard Model (MSSM) by right-handed neutrino and sneutrino states. The light sneutrino is then predominantly right-handed. Interestingly, this model is consistent with electroweak precision data and LEP limits on the mass of the lightest CP-even Higgs boson [7].

Yet the existence of a bottom squark  $\tilde{b}$  with a mass *below* the  $b$ -quark mass and the conjectured chargino-mediated semileptonic decay has a striking consequence: In such a scenario the neutralino-mediated decays  $b \rightarrow \tilde{b}\nu\tilde{\nu}^*$  and  $b \rightarrow \tilde{b}\bar{\nu}\tilde{\nu}$  are kinematically allowed. In the Standard Model, bottom quarks dominantly decay as  $b \rightarrow cX$ . Hence  $b$  decays are suppressed by the small element  $V_{cb} \approx 0.04$  of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. The new decay modes do not suffer from any CKM suppression and therefore have potentially large branching ratios. Since the light  $\tilde{b}$  decays only semileptonically, the supersymmetric decay channels increase the lepton yield in  $b$  decays through the cascade decay  $b \rightarrow \tilde{b}\mathbb{E} \rightarrow c\ell\mathbb{E}$ . Here  $\mathbb{E}$  denotes the missing energy from the (s)neutrinos. The measurement of the semileptonic branching ratio  $B_{SL} = Br(B \rightarrow X_{c\ell}\bar{\nu}_\ell)$ ,  $\ell = e, \mu$ , of  $B$  mesons is a mature field. At the  $B$  factory CLEO  $B, \bar{B}$  pairs are copiously produced from the  $\Upsilon(4S)$  resonance. The measurement of  $B_{SL}$  amounts to counting the leptons in the final states of  $B$ -decays. The presence of secondary leptons from non-leptonic  $B$  decays followed by a semileptonic decay of the decay products constitutes a background, which must be subtracted. The dilepton analysis by CLEO [8] subtracts this background using *measured* branching ratios and lepton spectra. Hence it is clear that the cascade decay  $b \rightarrow \tilde{b}\mathbb{E} \rightarrow c\ell\mathbb{E}$  would be ascribed to the signal rather than the background. The extra events also pass the low cut  $p_\ell \geq 600$  MeV on the lepton momentum in the  $B$  rest frame, although leptons from the supersymmetric cascade decays are softer than the primary leptons. The CLEO result  $B_{SL} = (10.49 \pm 0.46)\%$  [8] and the LEP measurement of  $Br(b \rightarrow c\ell\bar{\nu}_\ell) = (11.01 \pm 0.38)\%$  [9] are consistent with the Standard Model prediction of  $9.9\% \leq B_{SL} \leq 13\%$  [10,11].  $B_{SL}$  is the ratio of the semileptonic and the total rate. In the Standard Model the CKM element  $V_{cb}$  drops out from this ratio and  $B_{SL}$  depends only on Standard Model parameters whose values are unaffected by a light  $\tilde{b}$ .

In this letter we investigate the contributions to  $B_{SL}$  from  $b \rightarrow \tilde{b}[\rightarrow c\ell\tilde{\nu}^*]\nu\tilde{\nu}^*$  and  $b \rightarrow \tilde{b}[\rightarrow c\ell\tilde{\nu}^*]\bar{\nu}\tilde{\nu}$ . We calculate the rates of these bottom decays and the decay rate for  $\tilde{b} \rightarrow c\ell\tilde{\nu}^*$  in sect. II. In sect. III we correlate the  $\tilde{b}$  lifetime with the new contribution to  $B_{SL}$ . We scan over the values of the supersymmetric parameters entering the considered decay rates allowing for a non-vanishing sneutrino mass. Finally we conclude in sect. IV.

## II. DECAY RATES

As mentioned in the Introduction, we have to extend the MSSM by right-handed (s)neutrino states, because a purely left-handed light sneutrino would couple to the  $Z$  and would therefore contribute to the well-measured invisible  $Z$  width.<sup>1</sup> Phenomenological constraints from flavor-changing neutral currents further imply that the CKM matrix accompanying quark-squark-chargino vertices is the same as in the couplings of quarks to the  $W$  boson [13]. Hence the semileptonic  $\tilde{b}$  decay is governed by the same CKM element  $V_{cb} \approx 0.04$  as the standard semileptonic  $b$  decay. We further assume that there are two light sneutrino states corresponding to  $\tilde{\nu}_e$  and  $\tilde{\nu}_\mu$ , so that both semileptonic decays with  $\ell = e$  and  $\ell = \mu$  are

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<sup>1</sup>Still such a scenario with dominantly right-handed sneutrinos might contradict cosmological bounds [12] and one could need additional small R-parity violating couplings to allow the LSP sneutrino to decay.

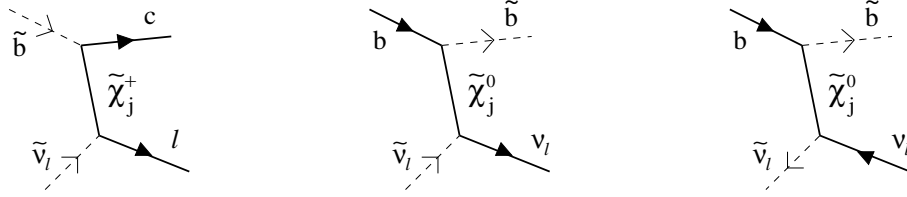


Figure 1. Semileptonic sbottom decay (left) and the decays  $b \rightarrow \tilde{b}\nu_l\tilde{\nu}_l^*$  (center) and  $b \rightarrow \tilde{b}\bar{\nu}_l\tilde{\nu}_l$  (right).  $l$  represents  $e$  or  $\mu$ .

possible. This assumption, however, does not influence the correlation between the sbottom lifetime and the branching ratio  $Br(b \rightarrow \tilde{b}\mathbb{P})$ , because it amounts to an overall factor of 2 for all relevant decay rates. We calculate all decay rates at the partonic level, in the tree level approximation of perturbation theory. Although  $b$  and  $\tilde{b}$  hadronize, the binding effects are suppressed by two powers of  $\Lambda_{QCD}/E$ , where  $E$  is the average energy release to the final state hadron [14]. We account for these power corrections and for contributions of uncalculated radiative corrections by conservatively inflating the allowed ranges for the input parameters in our phenomenological discussion in sect. III. Further, we remark that our formulae become inaccurate for sneutrino masses near the kinematic limit. In this case  $E = \mathcal{O}(\Lambda_{QCD})$ , and the final state hadron moves too slowly in the rest frame of the decaying hadron. Therefore naive perturbation theory breaks down. Yet we will see in sect. III that in this region it is hard to accommodate for the conjectured sbottom lifetime.

We denote the light sbottom and light sneutrino mass eigenstates by  $\tilde{b}_1$  and  $\tilde{\nu}_1$ . The mixing angle  $\theta_b$  relating  $\tilde{b}_1$  to scalar partners of the chiral  $b$ -fields is defined as  $\tilde{b}_1 = \cos\theta_b\tilde{b}_L + \sin\theta_b\tilde{b}_R$ , with an analogous definition for the sneutrino mixing angle  $\theta_\nu$ . We adopt the standard notation [15] for the MSSM mass parameters and mixing matrices: the chargino mass matrix is diagonalized as

$$\mathcal{M}_c = \begin{pmatrix} M_2 & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix} = U^T \text{diag}(m_{\tilde{\chi}_j^+}) V. \quad (1)$$

By convention  $M_2 > 0$  and  $\tilde{\chi}_1^+$  is the lighter chargino. Since we are not interested in CP violation here, we choose all mass matrices and the unitary mixing matrices  $U$  and  $V$  real.  $\tan\beta$  is the ratio of the Higgs vacuum expectation values. The neutralino mass matrix reads

$$\begin{pmatrix} M_1 & 0 & -m_Z s_w \cos\beta & m_Z s_w \sin\beta \\ 0 & M_2 & m_Z c_w \cos\beta & -m_Z c_w \sin\beta \\ -m_Z s_w \cos\beta & m_Z c_w \cos\beta & 0 & -\mu \\ m_Z s_w \sin\beta & -m_Z c_w \sin\beta & -\mu & 0 \end{pmatrix} = N^T \text{diag}(m_{\tilde{\chi}_j^0}) N, \quad (2)$$

where  $s_w, c_w$  are the sine and cosine of the weak mixing angle. We choose  $N$  as an orthogonal matrix. Then the mass eigenvalues can be negative and the physical neutralino masses are their absolute values.

The decay  $\tilde{b}_1 \rightarrow c\ell\tilde{\nu}_1^*$  is depicted in the left diagram of Fig. 1. The corresponding matrix element equals  $K\bar{c}P_R\ell$ , where  $P_R = (1 + \gamma_5)/2$  and

$$K = V_{cb}g \cos\theta_\nu \sum_{j=1}^2 \frac{V_{j1}}{m_{\chi_j}} [g \cos\theta_b U_{j1} - h_b \sin\theta_b U_{j2}]. \quad (3)$$

Here we have neglected the sbottom momentum in the chargino propagator and the small Yukawa coupling to  $\ell$ .  $g \simeq 0.65$  is the SU(2) gauge coupling and  $h_b$  is the bottom Yukawa coupling. Our result agrees with the expression in [16]. We conveniently re-express  $V_{jk}$ ,  $U_{jk}$  and  $m_{\tilde{\chi}_j^+}$  in terms of  $M_2$ ,  $\mu$  and  $\beta$ :

$$\sum_{j=1} V_{ji} \frac{1}{m_{\chi_j}} U_{jk} = [V^T D^{-1} U]_{ik} = [\mathcal{M}_c^{-1}]_{ik}. \quad (4)$$

Then eq. (3) becomes

$$K = V_{cb} g \cos \theta_\nu \frac{g \mu \cos \theta_b + \sqrt{2} h_b m_W \sin \theta_b \sin \beta}{M_2 \mu - m_W^2 \sin(2\beta)}. \quad (5)$$

A lifetime of  $\mathcal{O}(1 \text{ ps})$  [5] implies that the semileptonic decay rate of the light sbottom ( $\propto m_{b_1}^3 / m_{\tilde{\chi}_1^+}^2$ ) exceeds the rate of the  $b$  quark ( $\propto m_b^5 / m_W^4$ ) by roughly a factor of 7. To accommodate for this, one is naturally lead to the portion of the parameter space with a large Yukawa coupling  $h_b$  and thereby a large  $\tan \beta$ . In this region supersymmetric QCD corrections to the relation of  $h_b$  to  $m_b$  can be huge [17]. Yet such  $\tan \beta$  enhanced corrections can be summed to all orders [18]:

$$h_b = \frac{g}{\sqrt{2} m_W \cos \beta} \frac{m_b}{1 + \Delta m_b^{SQCD}} \quad (6)$$

with

$$\Delta m_b^{SQCD} = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan \beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}).$$

$$I(a, b, c) = \frac{1}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \left( a^2 b^2 \ln \frac{a^2}{b^2} + b^2 c^2 \ln \frac{b^2}{c^2} + c^2 a^2 \ln \frac{c^2}{a^2} \right).$$

Here  $m_{\tilde{g}}$  is the gluino mass. The strong coupling constant  $\alpha_s$  must be evaluated at a high scale of order  $m_{\tilde{g}}$  or  $m_{\tilde{b}_2}$ . Moreover, the light sbottom has to be included in the running of  $\alpha_s$ . The non-leading corrections to eq. (6) can be safely neglected [19]. The semileptonic decay rate now reads

$$\Gamma_{SL} = \Gamma(\tilde{b}_1 \rightarrow c \ell \tilde{\nu}_2) = \frac{|K|^2}{32 m_{\tilde{b}_1} \pi^5} p(m_{\tilde{b}_1}, m_c, m_{\tilde{\nu}}). \quad (7)$$

Since we assume that the two decay channels with  $\ell = e$  and  $\ell = \mu$  are allowed, the sbottom lifetime is given by  $\tau_{\tilde{b}} = 1/\Gamma_{tot} = 1/(2 \Gamma_{SL})$ . The phase space integral reads

$$p(M, m_1, m_2) = \int \frac{d^3 \vec{p}_1}{2E_1} \frac{d^3 \vec{p}_2}{2E_2} \frac{d^3 \vec{p}_3}{2E_3} \delta^{(4)}(P - p_1 - p_2 - p_3) p_1 \cdot p_3, = M^4 p\left(1, \frac{m_1}{M}, \frac{m_2}{M}\right) \quad (8)$$

with the masses  $p_3^2 = 0$ ,  $p_{1,2}^2 = m_{1,2}^2$  and  $P^2 = M^2$ . We find

$$p(1, x_1, x_2) = \frac{\pi^2}{8} \left[ x_1^4 (1 + x_2)^2 y \ln \frac{y + x}{y - x} + [4x_1^2 x_2^2 - (1 + x_2^2)(x_1^4 + 2x_2^2)] \ln \frac{1 + x}{1 - x} \right. \\ \left. + \frac{x [(1 + x_2)^2 - x_1^2]}{6} [1 + 10x_2^2 + x_2^4 - 5x_1^2 (1 + x_2^2) - 2x_1^4] \right]$$

$$\text{with } x = \sqrt{\frac{(1 - x_2)^2 - x_1^2}{(1 + x_2)^2 - x_1^2}}, \quad y = \frac{1 - x_2}{1 + x_2}.$$

$$p(1, x_1, 0) = \frac{\pi^2}{48} [(1 - x_1^2)(1 - 5x_1^2 - 2x_1^4) - 12x_1^4 \ln x_1]$$

Next we turn to the two neutralino-mediated decays  $b \rightarrow \tilde{b}_1 \nu \tilde{\nu}_1^*$  and  $b \rightarrow \tilde{b}_1 \bar{\nu} \tilde{\nu}_1$  in Fig. 1. The two different final states are possible because of the Majorana nature of the neutralinos. As for the sbottom decay we assume two light flavor-generations of neutrinos. The matrix element for  $b \rightarrow \tilde{b}_1 \nu \tilde{\nu}_1^*$  can be written as  $K_R \bar{\nu} P_R b$  and the amplitude for  $b \rightarrow \tilde{b}_1 \bar{\nu} \tilde{\nu}_1$  is of the form  $K_L \bar{\nu} P_L b$  with  $P_L = (1 - \gamma_5)/2$ . The coefficients are

$$\begin{aligned} K_R &= g \cos \theta_\nu \sum_{j=1}^4 \frac{N_{j2} - N_{j1} t_w}{m_{\chi_j^0}} \left[ \frac{g}{3} t_w \sin \theta_b N_{j1} + \frac{h_b}{\sqrt{2}} \cos \theta_b N_{j3} \right] \\ &= -\frac{g \cos \theta_\nu}{d} \left[ g \mu^2 \frac{M_2 t_w^2}{3} \sin \theta_b + \frac{h_b}{\sqrt{2}} \mu m_W \sin \beta \cos \theta_b (M_1 + M_2 t_w^2) \right] \end{aligned} \quad (9)$$

$$\begin{aligned} K_L &= g \cos \theta_\nu \sum_{j=1}^4 \frac{N_{j2} - N_{j1} t_w}{m_{\chi_j^0}} \left[ \frac{g}{2} \cos \theta_b \left( \frac{t_w}{3} N_{j1} - N_{j2} \right) + \frac{h_b}{\sqrt{2}} \sin \theta_b N_{j3} \right] \\ &= -\frac{g \cos \theta_\nu}{d} \left[ g \mu^2 \left( \frac{M_2 t_w^2}{6} + \frac{M_1}{2} \right) \cos \theta_b + \frac{h_b}{\sqrt{2}} \mu m_W \sin \beta \sin \theta_b (M_1 + M_2 t_w^2) \right]. \end{aligned} \quad (10)$$

$t_w$  is given by  $\tan \theta_w = s_w/c_w$ , and  $-d$  is the determinant of the neutralino mass matrix in eq. (2):

$$d = \mu \left[ M_1 M_2 \mu - m_W^2 \sin(2\beta) (M_1 + M_2 t_w^2) \right].$$

The couplings given in eq. (9) and eq. (10) nicely reveal that the term proportional to  $h_b$  is zero for  $M_1 = -M_2 t_w^2$ . In this case the  $\tilde{Z} \tilde{H}_1$  element of the inverse neutralino mass matrix vanishes. Then the Higgsino  $\tilde{H}_1$ , which couples with  $h_b$  to the  $b$  and  $\tilde{b}$ , cannot propagate into the Zino, which is the only gauge fermion coupling to the  $\nu$ - $\tilde{\nu}$  line. By comparing eq. (9) and eq. (10) with eq. (5) one can also identify the terms in the sbottom and bottom decay amplitudes which are related by electroweak SU(2) symmetry. The SU(2) symmetry leads to a high correlation between the two decay modes: if one picks SUSY parameters keeping  $K$  large enough to accommodate the lifetime observed in [5], one cannot simultaneously make both  $K_R$  and  $K_L$  arbitrarily small.

After summing the decay rates for the two decay modes, each lepton flavor  $\ell = e, \mu$  gives a new contribution to the bottom width of

$$\Delta \Gamma \equiv \Gamma(b \rightarrow \tilde{b}_1 (\nu \tilde{\nu}_1^* + \bar{\nu} \tilde{\nu}_1)) = \frac{|K_R|^2 + |K_L|^2}{64 m_b \pi^5} q(m_b, m_{\tilde{b}_1}, m_{\tilde{\nu}_1}). \quad (11)$$

Here the space space integral reads

$$q(M, m_1, m_2) = \int \frac{d^3 \vec{p}_1}{2E_1} \frac{d^3 \vec{p}_2}{2E_2} \frac{d^3 \vec{p}_3}{2E_3} \delta^{(4)}(P - p_1 - p_2 - p_3) P \cdot p_3 = M^4 q(1, x_1, x_2), \quad (12)$$

where again  $p_3^2 = 0$ ,  $p_{1,2}^2 = m_{1,2}^2$  and  $P^2 = M^2$ . We calculate

$$\begin{aligned}
q(1, x_1, x_2) &= \frac{\pi^2}{8} \left[ (x_1 - x_2)^2 y \ln \frac{y+x}{y-x} - [x_1^2 + x_2^2 - 4x_1^2 x_2^2 + 2x_1^4 x_2^2 + 2x_1^2 x_2^4] \ln \frac{1+x}{1-x} \right. \\
&\quad \left. + \frac{x [1 - (x_1 - x_2)^2]}{6} [2 + 5x_1^2 + 5x_2^2 - x_1^4 - x_2^4 - 10x_1^2 x_2^2 - x_2^4] \right] \\
&\quad \text{with } x = \sqrt{\frac{1 - (x_1 + x_2)^2}{1 - (x_1 - x_2)^2}}, \quad y = \frac{x_1 + x_2}{x_1 - x_2}. \\
q(1, x_1, 0) &= \frac{\pi^2}{48} \left[ (1 - x_1^2)(2 + 5x_1^2 - x_1^4) + 12x_1^2 \ln x_1 \right].
\end{aligned}$$

In a  $B$ -factory like CLEO the  $B$  mesons move too slowly to resolve a displaced vertex from the  $\tilde{b}_1$  in the cascade decay  $b \rightarrow \tilde{b}_1 \mathbb{E} \rightarrow c \ell \mathbb{E}$ . Hence the signal of a  $b$  decay into a light sbottom would basically be an increase of the semileptonic branching ratio  $B_{SL}$  and a shift of the lepton spectrum to lower energies as discussed in the Introduction. Therefore it is useful to normalize  $\Delta\Gamma$  to the semileptonic decay rate  $\Gamma_{SL}$  of the  $B$  meson (which to order  $\Lambda_{QCD}^2/m_b^2$  coincides with the semileptonic decay rate of the  $b$  quark [14]). The experimental value for  $\Gamma_{SL}$  is obtained by dividing the measured  $B_{SL} = (10.49 \pm 0.46)\%$  [8] by the measured lifetime  $\tau_B = 1.55 \pm 0.03 \text{ ps}^{-1}$  [20]:

$$\Gamma_{SL} = \Gamma(B \rightarrow X_{\bar{c}} \ell^+ \nu_{\ell}) = (4.45 \pm 0.21) \cdot 10^{-14} \text{ GeV}$$

per lepton flavor  $\ell = e$  or  $\mu$ . SUSY parameters yielding  $\Delta\Gamma > 5$  are already excluded from the measured  $B$  lifetime alone: since the total branching ratio into light leptons is  $2B_{SL} \simeq 20\%$ ,  $\Delta\Gamma$  would exceed the total decay rate  $1/\tau_B$  in these scenarios. We further remark that the decay mode  $b \rightarrow \tilde{b}_1 \mathbb{E} \rightarrow c \ell \mathbb{E}$  would also influence the determination of  $V_{cb}$ , which enters our analysis of the sbottom lifetime, from inclusive semileptonic decays. The true value of  $V_{cb}$  would be somewhat lower than the Standard Model value of 0.04 and our exclusion plots in the following section would become even more restrictive. On the other hand, measurements of  $V_{cb}$  from exclusive decays near the kinematic endpoint are less affected because of the softer leptons from the supersymmetric decays.

### III. MSSM PARAMETER SPACE

To determine how the semileptonic sbottom and the bottom decay widths are related, we perform an MSSM parameter scan: for all models leading to a sbottom lifetime between 0.5 and 2 ps we compute the additional semileptonic bottom decay width  $\Delta\Gamma$  and compare it to the measured value, as shown in Fig. 2(a,b). In the scan we assume a sbottom mass of 3.5 GeV and fix the presumably small [5] sneutrino LSP mass to 0.3 GeV. Disregarding the large theoretical errors we emphasize that the results of the analysis become dependent on the sneutrino mass only close to threshold. For reasons discussed below, the case  $\mu > 0$  hardly ever leads to a sbottom lifetime below 2 ps, whereas  $\mu < 0$  generates a rich variety of scenarios. In particular, the case  $\mu > 0$  cannot accommodate sneutrino masses above 0.5 GeV.

We note that all Yukawa couplings contributing to the considered decays are enhanced by  $\tan\beta$ . *i.e.* to reach the measured sbottom lifetime one is automatically driven into the large  $\tan\beta$  regime. We in fact observe that varying all other input parameters in the given ranges only allows values of  $\tan\beta > 15$  for  $\mu < 0$  and  $\tan\beta > 25$  for  $\mu > 0$ . As an upper limit we choose  $\tan\beta = 60$ . Since both the bottom and the

sbottom decay widths are enhanced, the minimal  $\Delta\Gamma$  in the scan depends only weakly on the value of  $\tan\beta$  in the given interval.

The parameters determining the masses of the virtual charginos and neutralinos are  $M_2$  and  $\mu$ . In addition the Higgsino mass parameter enters into the correction to the bottom Yukawa coupling: for positive values of  $\mu$  the mass correction  $\Delta m_b$  is positive, leading to a decrease in  $h_b$  and therefore a decrease in the sbottom decay width until the gaugino coupling to the sbottom becomes dominant, at the expense of the total decay width. For  $\mu < 0$  the mass correction becomes negative. Values around  $\Delta m_b = -1$  dramatically increase the Yukawa coupling<sup>2</sup>. A comparison of scenarios with the two signs of  $\mu$  in Fig. 2(a,b) shows that the impact of the increased Yukawa coupling leads to an enhancement by a factor of two in the typical sbottom lifetime.

Since the sbottom decays through a virtual chargino, either  $M_2$  or  $|\mu|$  has to be sufficiently small, to keep the suppression moderate. For  $\mu > 0$  both parameters  $|\mu|$  and  $M_2$  have to be smaller than 400 GeV. The light chargino mass, which we require to respect the LEP lower limit of 103 GeV<sup>3</sup>, is found to be smaller than 140 GeV. In the less constrained case of  $\mu < 0$  only  $M_2$  has a strict upper limit of 500 GeV, but large values of  $|\mu| \gtrsim 500$  GeV require  $M_2 \lesssim 250$  GeV. The upper limit for the mass of the light chargino becomes 350 GeV. We vary the additional Bino mass parameter  $M_1$  between  $\mp 1$  TeV to always cover the decoupling point  $M_1 = -M_2 t_w^2$ , as described in sect.II. In Fig.2(c,d) we show that  $\Delta\Gamma < 50\Gamma_{SL}$  can only be achieved for parameters close to this decoupling point. In particular for the Yukawa coupling dominated models with  $\mu < 0$  we observe a sharp decrease in the minimum value for  $\Delta\Gamma$ . The numerical width of the allowed parameter region is shown in Fig. 2(e,f). With  $\cos\theta_b \sim 1.0$  the  $\bar{\nu}\tilde{\nu}_1$  decay channel dominates. For  $M_1 = -M_2 t_w^2$  the Yukawa contribution vanishes, and the corresponding gauge coupling proportional to  $\sin\theta_b$  leads to negligible values of  $\Delta\Gamma$ . In the other decay channel  $\nu\tilde{\nu}_1^*$  the gauge coupling is enhanced by  $\cos\theta_b$  and thereby rescues the total MSSM contribution to the semileptonic decay width. However, typical values of  $\Delta\Gamma$  become significantly smaller, in particular for  $\mu < 0$ , where the large bottom Yukawa coupling was further enhanced. By contrast, models sufficiently separated from the decoupling point easily yield an enhancement of several hundred times the Standard Model value of  $\Gamma_{SL}$ .

The sbottom and the sneutrino mixing angle are constrained by the measurement of the  $Z$  width: both particles have to decouple from the  $Z$  boson. A right-handed LSP sneutrino does indeed not couple to the  $Z$ . However, it does not couple to the intermediate chargino in the sbottom decay either. We therefore assume a fraction of left-handedness in the LSP, parameterized by  $\cos\theta_\nu < 0.2$ . A small fraction of left-handedness might be a hint for a see-saw mechanism in the scalar neutrino mass matrix. Since both the bottom and the sbottom decay width scale with the square of this fraction, we have checked that reducing  $\cos\theta_\nu$  does not affect the result, until it suppresses the sbottom decay widths too strongly to allow for any models with a lifetime  $\tau_b < 2$  ps.

The light sbottom decouples from the  $Z$  for a leading order mixing angle of  $|\cos\theta_b| = s_w\sqrt{2/3}$ , *i.e.* a mixture of left and right-handed states aligned with the weak mixing angle. Taking into account possible experimental uncertainties we impose  $0.8 < |\sin\theta_b| < 1.0$ . Since the Yukawa coupling to the chargino is dominant in most of our valid models, the mixing angle strongly affects the sbottom decay width. A completely right-handed sbottom is preferred, because it gives the Yukawa coupling a maximal relative

<sup>2</sup>Models with  $h_b^2/(4\pi^2) > 1$  we reject as non-perturbative.

<sup>3</sup>This limit is based on a neutralino LSP scenario, but the sneutrino LSP does hardly change the signature and leads to an increased production cross section. We therefore assume a chargino mass limit close to the kinematical limit [21].

weight. However, the Majorana nature of the neutralino allows the two decay modes in Fig. 1, which couple to either the right-handed or the left-handed sbottom states. Therefore  $\cos\theta_b = 1$  also leads to an enhancement of the respective decay channel, while suppressing the other. Even at the decoupling point  $M_1 = -M_2 t_w^2$  it is impossible to switch off both decays simultaneously.

#### IV. CONCLUSIONS

We have investigated implications of recently reported experimental hints for a light sbottom squark  $\tilde{b}$  with a mass below  $m_b$  and a lifetime around 1 picosecond decaying as  $\tilde{b} \rightarrow c\ell\tilde{\nu}^*$ . We have studied the decay modes  $b \rightarrow \tilde{b}\nu\tilde{\nu}^*$  and  $b \rightarrow \tilde{b}\bar{\nu}\tilde{\nu}$ , which are related to the semileptonic sbottom decay by electroweak SU(2) symmetry. At  $B$ -factories these decay modes would manifest themselves through the cascade decay  $b \rightarrow \tilde{b}\mathbb{E} \rightarrow c\ell\mathbb{E}$  and would increase the well-measured semileptonic branching ratio  $B_{SL}$  of  $B$  mesons. We have determined the correlation between the sbottom lifetime and the rates of these supersymmetric  $b$  decays. A scan over the entire MSSM parameter space has shown that the rate of  $b \rightarrow \tilde{b}\mathbb{E}$  typically exceeds the semileptonic bottom decay rate  $\Gamma_{SL}$ . It easily reaches values which are up to 1000 times the experimental value  $\Gamma_{SL} = B_{SL}/\tau_B$ . The minimal value is  $\Gamma(b \rightarrow \tilde{b}\mathbb{E}) \approx 1.4\Gamma_{SL}$  for  $\mu < 0$  and  $\Gamma(b \rightarrow \tilde{b}\mathbb{E}) \approx 7\Gamma_{SL}$  for  $\mu > 0$ . Both are obtained for large values of the bottom Yukawa coupling. The minimal values of  $\Gamma(b \rightarrow \tilde{b}\mathbb{E})$  correspond to a small region of the supersymmetric parameter space in which a Zino-Higgsino mixing term in the neutralino sector vanishes. In view of the the good agreement of the measured  $B_{SL}$  with the Standard Model prediction we conclude that experimental anomalies reported in [5,6] cannot be interpreted as light sbottoms decaying as  $\tilde{b} \rightarrow c\ell\tilde{\nu}^*$ , unless the decays  $b \rightarrow \tilde{b}\nu\tilde{\nu}^*$  and  $b \rightarrow \tilde{b}\bar{\nu}\tilde{\nu}$  are kinematically forbidden.

We remark here that our reasoning similarly constrains a light sbottom interpretation of the anomalies of [5,6], if the sbottom is *heavier* than the bottom quark. If the decays  $\tilde{b} \rightarrow b\nu\tilde{\nu}^*$  and  $\tilde{b} \rightarrow b\bar{\nu}\tilde{\nu}$  are kinematically allowed, they will by far be the dominant decay modes in most of the supersymmetric parameter space and the observed decay  $\tilde{b} \rightarrow c\ell\tilde{\nu}^*$  would be rare. This would point at a much higher sbottom production rate and we presume that the secondary vertices from the  $\tilde{b}$  and  $b$  in these  $\tilde{b} \rightarrow b\mathbb{E}$  decays would have been detected in collider experiments. While a detailed study of this scenario is beyond the scope of this letter, we also consider this possibility as remote. The anomalies reported in [5] are essentially only compatible with a light sbottom interpretation, if  $|m_b - m_{\tilde{b}_1}| \leq m_{\tilde{\nu}_1}$ .

Even if we leave the framework of supersymmetry, it is hard to relate the experimental anomalies to some other bottom-flavored object. Consider any new SU(2)-invariant renormalizable model with conserved lepton number: the semileptonic decay mode will then have the topology of the left diagram in Fig. 1. By SU(2) symmetry then  $b$  decays corresponding to the middle diagram are allowed. The suppression of this decay mode would involve fine tuning of the left and right-handed  $b$  flavor components and between the U(1) and SU(2) gauge sectors.

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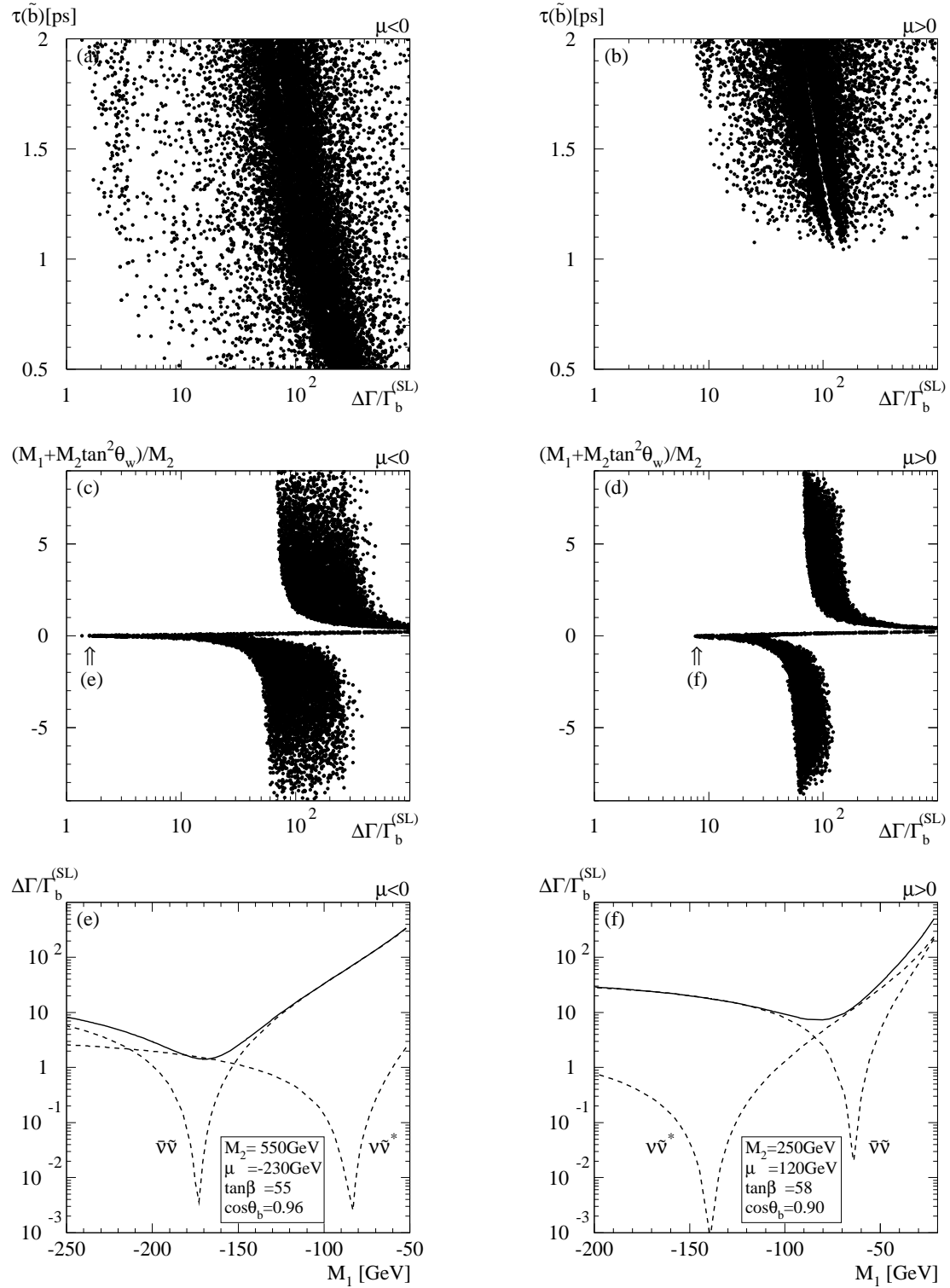


Figure 2. The contribution of  $b \rightarrow \tilde{b} + \mathbb{E} \rightarrow c \ell \mathbb{E}$  to the semileptonic  $b$  decay in 20000 MSSM scenarios, all fulfilling the relaxed sbottom lifetime requirement of  $\tau_{\tilde{b}} < 2 \text{ ps}$  (left:  $\mu < 0$ , right:  $\mu > 0$ ). The SUSY bottom decay width is plotted versus the sbottom lifetime (a,b) and versus the relevant combination of gaugino masses (c,d). For two particular parameter points the variation of the different decay channels with  $M_1$  is shown (e,f).